

Smart Reactive Power Management Using FACTS Controllers for Stable and Efficient Power System Operation

B. Kishore¹; S. Vishwa Teja²; N. Ramakrishna³; S. Umesh⁴; B. Sharath⁵;
B. Varshith⁶

^{1,2,3,4,5,6}BE, IV Year, Department of Electrical and Electronics Engineering, Methodist College of Engineering and Technology (Autonomous), Hyderabad, India

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Abstract: Modern power systems face increasing challenges in maintaining voltage stability, improving power transfer capacity, and reducing transmission losses due to growing electricity demand and limited infrastructure expansion. Reactive power management has emerged as a critical factor in addressing these challenges, as uncontrolled reactive power leads to voltage fluctuations, reduced equipment utilization, increased line losses, and potential system instability. This paper presents a comprehensive examination of reactive power compensation techniques utilizing Flexible AC Transmission System (FACTS) controllers, which represent a paradigm shift from conventional mechanical compensation methods to advanced power electronic-based solutions. FACTS controllers provide dynamic, fast-acting control of transmission system parameters through power electronic switching devices, enabling real-time reactive power compensation without the limitations of traditional mechanical systems. This paper investigates various FACTS controller topologies including Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC), and Unified Power Flow Controller (UPFC), analyzing their operational principles, control strategies, and performance characteristics in both shunt and series compensation configurations. The study demonstrates how FACTS controllers enhance power system stability by maintaining voltage profiles within acceptable limits, damping power oscillations, improving power factor, and increasing the load ability of existing transmission corridors without requiring costly infrastructure expansion. Through theoretical analysis and system modeling, this paper evaluates the effectiveness of different FACTS devices in various power system scenarios, comparing their technical benefits, economic viability, and application suitability. The findings indicate that strategic deployment of FACTS controllers offers significant advantages in terms of improved system efficiency, enhanced reliability, and deferred capital investment in new transmission facilities, making them essential components of modern smart grid infrastructure.

Keywords: Power Systems, Flexible AC Transmission Systems, Voltage Sources Converters, Shunt Controllers, Series Controllers, Reactive Power Compensation, Power Quality.

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I. INTRODUCTION

The electric power system represents one of the most complex and critical infrastructures of modern civilization, responsible for delivering reliable electrical energy to millions of consumers across vast geographical regions. As global electricity demand continues to escalate due to rapid industrialization, urbanization, and the proliferation of energy-intensive technologies, power systems worldwide face unprecedented challenges in maintaining operational stability, efficiency, and reliability. Among the multifaceted technical challenges confronting power system engineers, reactive power management and voltage stability have emerged as

particularly critical concerns that directly impact system performance, power quality, and the prevention of catastrophic failures such as voltage collapse and widespread blackouts[1]-[2].

Reactive power, measured in volt-amperes reactive (VAR), represents the imaginary component of AC power that does not perform useful work but is essential for maintaining voltage levels and enabling the transmission of active power through electrical networks. Unlike active power which flows unidirectionally from generators to loads, reactive power oscillates between sources and reactive elements such as inductors and capacitors, creating a complex dynamic that

must be carefully managed to ensure system stability. The presence of inductive loads in industrial applications, including motors, transformers, and arc furnaces, causes the current waveform to lag behind the voltage waveform, resulting in a lagging power factor and increased demand for reactive power. When reactive power is inadequately managed, numerous detrimental consequences emerge that compromise both the technical and economic performance of power systems.[3]-[4].

The problems associated with improper reactive power management manifest in multiple forms, each contributing to overall system degradation. Excessive reactive power flow significantly increases the drawn current for any given load level, which in turn amplifies resistive losses in transmission lines, transformers, and other network components, resulting in reduced efficiency and wasted energy resources. These increased losses translate directly into higher operational costs for utilities and ultimately impact electricity prices for end consumers. Furthermore, inadequate reactive power support leads to voltage instability, characterized by voltage fluctuations, sags, or progressive decline that can culminate in voltage collapse—a phenomenon where the transmission network loses its ability to maintain acceptable voltage levels, potentially triggering cascading failures and widespread power outages affecting millions of customers.[5]-[6].

Ultimately, the modernization of power systems reflects a global pursuit of sustainable development. It aims to provide affordable, reliable, and clean electricity for all while mitigating environmental impacts. This paper delves into emerging technologies and trends shaping the future of power systems and examines the challenges and opportunities they bring to engineers, policymakers, and stakeholders worldwide[7]-[8].

The global electrical power system is undergoing a revolutionary transformation driven by the twin imperatives of sustainability and technological innovation. Traditional centralized grids, once dominated by large fossil-fuel-based generation units, are evolving into complex, intelligent, and decentralized networks integrating renewable energy sources, digital controls, and advanced communication systems. This evolution is not merely a technical shift but a paradigm change that encompasses economic, environmental, and social dimensions. The growing energy demand due to industrialization, urbanization, and digital connectivity has placed enormous pressure on conventional energy infrastructure. At the same time, the urgent need to mitigate climate change has accelerated the global transition toward low-carbon energy systems. Consequently, modern electrical power systems are being redesigned to incorporate renewable generation, electric mobility, smart grids, and energy storage technologies. These advancements are reshaping how electricity is generated, transmitted, distributed, and utilized. As a result, the power sector is becoming more flexible, efficient, and resilient, setting the foundation for sustainable development in the coming decades. The convergence of power electronics, artificial intelligence, and communication technologies is further enabling a dynamic and intelligent

electricity ecosystem, capable of responding in real time to variations in generation and demand[9]-[10].

Flexible Alternating Current Transmission System (FACTS) controllers are an innovative family of power-electronic-based devices designed to enhance the controllability, stability, and efficiency of AC power transmission systems. Originating from advancements in high-voltage direct current (HVDC) technologies, FACTS controllers leverage the capabilities of modern semiconductor devices to regulate power flow, voltage, and reactive power dynamically within electrical networks. Unlike traditional mechanical or passive devices such as capacitors, reactors, and phase-shifting transformers, FACTS devices utilize swift and precise switching mechanisms that operate within a fraction of an AC cycle, thereby providing real-time control and flexibility. This allows power systems to operate closer to their theoretical limits without compromising stability or reliability, optimizing existing infrastructure and deferring the costs and complexities associated with constructing new transmission lines or substations[11]-[12].

FACTS controllers are broadly categorized into shunt, series, and combined series-shunt types, each designed to target specific parameters within the power system. Shunt controllers like Static VAR Compensators (SVC) and Static Synchronous Compensators (STATCOM) primarily provide reactive power compensation and voltage support by injecting current in parallel with the transmission line. Series controllers such as the Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC) modify the line impedance by injecting voltage in series, thus controlling power flow and mitigating stability problems caused by line congestion. The combination of shunt and series functionalities in devices like the Unified Power Flow Controller (UPFC) provides unparalleled control over voltage magnitude, phase angle, and impedance simultaneously, enabling comprehensive management of active and reactive power flows. These controllers work synergistically to reduce power losses, enhance voltage stability, and damp power oscillations, facilitating more reliable grid operation under highly variable and stressed conditions.[13]-[14].

A critical advantage of FACTS controllers is their ability to improve both steady-state and dynamic performance of power systems. In steady-state operations, they allow secure loading of transmission lines nearer to their thermal limits by regulating power flows and mitigating undesirable reactive power circulation. This leads to more efficient utilization of existing lines and delays expensive infrastructure upgrades. During transient events such as faults, sudden load changes, or generator outages, FACTS devices react instantaneously to stabilize voltage and power flows, reducing the risk of cascading outages and blackouts. Their fast response and high controllability address challenges like voltage collapse, sub-synchronous oscillations, and transient instability, which are common in complex and heavily loaded transmission networks. Consequently, FACTS controllers have become vital tools for maintaining grid resilience and ensuring continuous power supply in modern electric power systems[15]-[16].

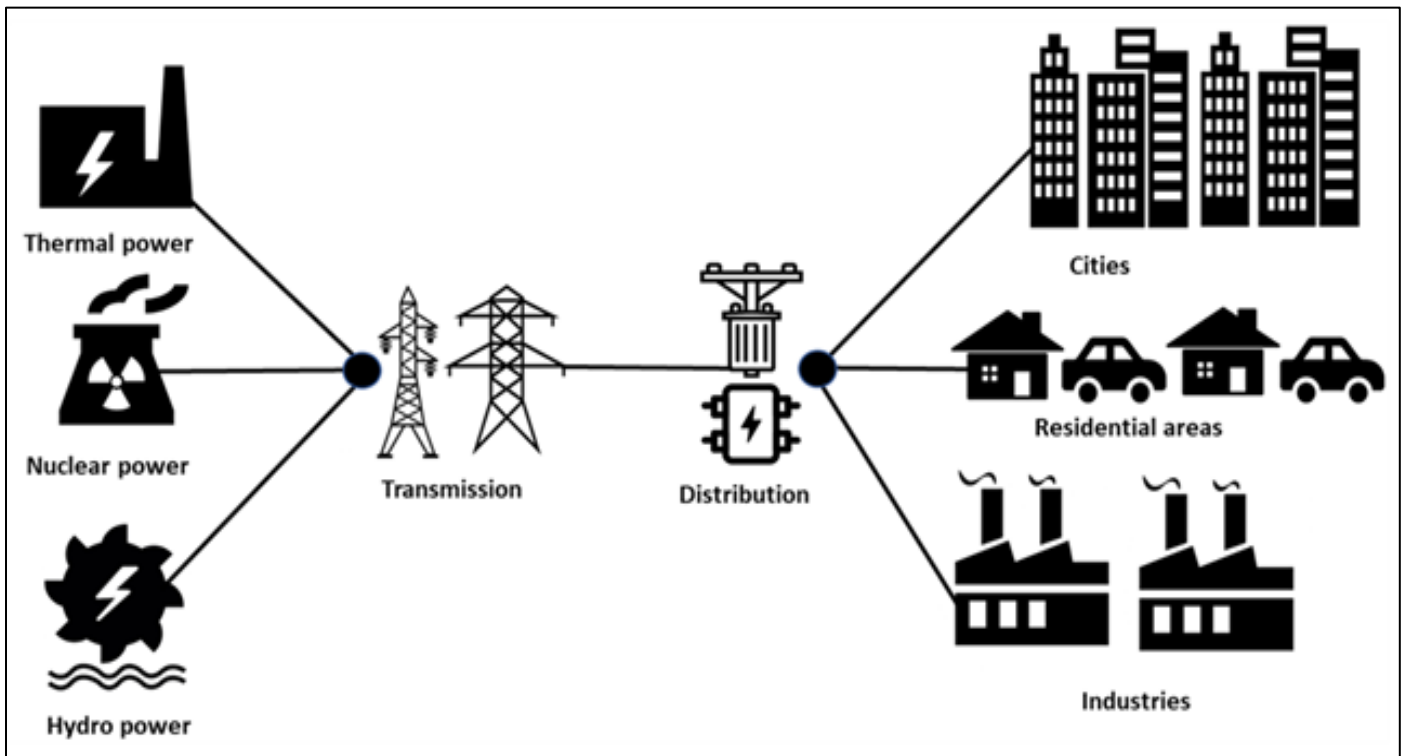


Fig 1 Traditional Thread of Power Systems

The emerging trends in electrical power systems present unprecedented opportunities for innovation, investment, and research. The global energy transition is fostering new business models, such as prosumer-based markets, virtual power plants, and energy-as-a-service (EaaS) frameworks. Moreover, the growing emphasis on energy sustainability and decarbonization is driving government policies, regulatory reforms, and international collaborations aimed at achieving net-zero emissions. Developing nations are particularly poised to benefit from these trends by leapfrogging to modern, decentralized, and renewable-based infrastructures without the constraints of legacy systems. Nevertheless, several challenges remain, including the need for massive infrastructure investments, standardization, and skilled workforce development. Ensuring system reliability, cybersecurity, and affordability in the face of rapid technological change is equally critical. Research in advanced power electronics, grid automation, and hybrid energy systems continues to open new frontiers for innovation. The future of electrical power systems will likely be characterized by high levels of automation, renewable dominance, and consumer participation. As the global community moves toward a more sustainable and digitally connected energy ecosystem, the integration of intelligent control, resilient infrastructure, and environmentally conscious technologies will define the next era of power system development. These transformations not only promise to deliver clean, reliable, and efficient energy but also to catalyze economic growth and environmental stewardship worldwide[17]-[18].

The proliferation of renewable energy sources, distributed generation, and deregulated electricity markets has further underscored the importance of FACTS technologies. The intermittent and variable nature of renewable generation

such as wind and solar introduces fluctuations and uncertainties in power flows, which can threaten grid stability. FACTS controllers mitigate these issues by providing rapid voltage support and adaptive power flow control, facilitating better integration of renewables and enabling the transition to more sustainable energy systems. Moreover, deregulated markets often operate transmission networks nearer to their operational limits for economic reasons, where FACTS devices offer critical support in optimizing power flows and preventing reliability violations. The continual evolution of semiconductor devices and control algorithms has expanded the versatility, efficiency, and cost-effectiveness of FACTS technologies, making them indispensable components in the smart grids of the future[19].

FACTS controllers represent a transformative evolution in electrical power system engineering, offering flexible, dynamic, and efficient control over power flow, voltage, and system stability. Their deployment enhances transmission capacity, increases operational reliability, and supports the integration of renewable resources, all while minimizing environmental and economic costs associated with network expansion. The rapid advancements in power electronics and control strategies continue to extend the capabilities of FACTS devices, positioning them as essential enablers for the evolving challenges and complexities of modern and future power systems. As grids become more interconnected and complex, the strategic implementation of FACTS technology will be pivotal to achieving resilient, sustainable, and economically optimized electrical energy delivery[20].

The problem is further exacerbated by certain types of equipment such as induction motors, tap-changing transformers, distribution voltage regulators, and thermostatic

loads which, during normal operation, attempt to restore consumed power but can inadvertently contribute to voltage instability during system disturbances. When voltage levels drop below acceptable thresholds, sensitive equipment malfunctions, industrial processes are disrupted, and in severe cases, generators may lose synchronism, leading to tripping of transmission lines and cascading outages. Conversely, excessive reactive power presents its own set of challenges. When reactive power supply significantly exceeds demand, the grid becomes over-excited, causing voltage levels to rise above normal operating ranges. This overvoltage condition can cause insulation breakdown in equipment not designed for elevated voltages, increase stress on power system components, and reduce equipment lifespan. Additionally, excessive reactive power can contribute to resonance phenomena where certain frequencies resonate with the grid's natural frequencies, resulting in increased harmonic distortions, power quality degradation, and additional equipment stress. Both insufficient and excessive reactive power scenarios lead to reduced grid capacity, as the transmission system's ability to deliver active power becomes constrained by reactive power imbalances[21], [22].

Historically, power system operators addressed reactive power compensation using conventional mechanical devices such as fixed capacitor banks, reactor banks, and synchronous condensers. While these traditional solutions provided static reactive power support, they suffered from significant limitations including slow response times, limited controllability, high maintenance requirements, and inability to provide continuous dynamic compensation matching the rapidly varying load conditions characteristic of modern power systems. The mechanical nature of switching operations in these devices prevented them from responding effectively to fast transients and system disturbances, leaving networks vulnerable to voltage instability during critical periods. The recognition of these limitations, combined with the increasing complexity and loading of transmission networks, catalyzed intensive research and development efforts beginning in the 1970s aimed at developing advanced power electronic-based solutions for reactive power control[23], [24].

II. OBJECTIVES

➤ *Comprehensive Understanding of Reactive Power Compensation*

In modern electrical power systems, the efficient transmission and utilization of electrical energy depend heavily on maintaining an appropriate balance between active and reactive power. While active power (measured in watts) performs the useful work such as lighting lamps or driving motors, reactive power (measured in vars) is essential for establishing magnetic and electric fields in inductive and capacitive equipment. Reactive power does not perform any network but is indispensable for voltage control, power-factor correction, and the stability of the system. However, excessive or deficient reactive power leads to undesirable voltage deviations, poor power-factor, increased transmission losses, and reduced system stability margins. Therefore, reactive power compensation has become a vital aspect of

modern power-system operation, aimed at controlling voltage profiles, enhancing power-transfer capability, minimizing losses, and improving overall system reliability. Traditionally, reactive power compensation was achieved using fixed or mechanically switched capacitors and reactors. However, with the advent of power-electronics technology, particularly high-power thyristors and voltage-source converters, a new generation of fast and continuously controllable compensation devices emerged under the umbrella of Flexible AC Transmission Systems (FACTS). FACTS controllers represent a revolutionary step in power-system engineering by providing dynamic control of power flows and voltage levels through rapid modulation of network parameters such as line impedance, phase angle, and bus voltage magnitude[25], [26].

The fundamental concept of reactive power compensation lies in the regulation of reactive-power flow within the system to maintain voltages within desired limits and improve the power factor. When an inductive load such as a motor or transformer consumes reactive power, the current lags behind the voltage, leading to a lagging power factor. This causes higher line currents for the same active-power transfer, thereby increasing copper losses and reducing voltage at the receiving end. Conversely, when capacitive compensation is introduced, it supplies leading reactive power locally, thereby offsetting the lagging component, improving voltage regulation, and reducing line current. Similarly, in cases where the system experiences over-voltage conditions due to capacitive effects, inductive compensation can be used to absorb excess reactive power and stabilize voltage. Hence, reactive-power compensation can be shunt, series, or combined, depending on how the compensating device is connected and what control objective it serves. The shunt devices primarily control bus voltage and reactive-power flow by injecting or absorbing reactive current, whereas series devices control line current and power flow by altering the effective line impedance or phase angle. Combined controllers, on the other hand, integrate both series and shunt functions to achieve comprehensive system control[27].

Before the introduction of FACTS technology, the reactive power in transmission systems was controlled through mechanically switched capacitors (MSCs), mechanically switched reactors (MSRs), and synchronous condensers. While these methods provided basic compensation, their response time was slow (in the order of seconds), and mechanical wear and tear limited their reliability and flexibility. As transmission networks expanded in size and complexity, and as utilities sought to operate lines closer to their thermal and stability limits, it became clear that traditional compensation devices were insufficient for modern dynamic requirements. This challenge led to the development of FACTS devices, which utilize high-speed power-electronic switches such as thyristors, gate-turn-off thyristors (GTOs), insulated-gate bipolar transistors (IGBTs), and modular multilevel converter (MMC) structures to provide continuously variable control with response times in milliseconds. FACTS technology, promoted by the IEEE Power Engineering Society, represents a paradigm shift from

passive compensation to active and dynamic control of AC power transmission systems[28].

Among the various categories of FACTS controllers, the shunt type plays a dominant role in reactive-power compensation and voltage stabilization. The two most prominent shunt FACTS devices are the Static Var Compensator (SVC) and the Static Synchronous Compensator (STATCOM). The SVC is a thyristor-based device composed primarily of a combination of Thyristor-Controlled Reactors (TCRs) and Thyristor-Switched Capacitors (TSCs) connected in parallel. By varying the firing angle of the thyristors, the current through the reactor branch can be continuously adjusted, thereby altering the net reactive power output of the SVC. When system voltage decreases, the SVC operates in capacitive mode to inject reactive power and restore voltage. Conversely, when voltage rises, it operates in inductive mode to absorb reactive power. This continuous control helps maintain voltage stability under varying load conditions. The main advantages of SVCs include simplicity, mature technology, and cost-effectiveness, making them suitable for medium-voltage substations and industrial systems. However, their dynamic response is limited by the nature of thyristor switching, and their performance deteriorates at low system voltages where the reactive current is proportional to the bus voltage magnitude. The STATCOM, in contrast, represents a more advanced generation of shunt compensation technology. It employs a voltage-source converter (VSC) to synthesize a controllable AC voltage from a DC capacitor source. By adjusting the converter output voltage magnitude relative to the system voltage, the STATCOM can supply or absorb reactive current almost instantaneously. If the converter voltage exceeds the system voltage, it supplies reactive power (capacitive mode); if it is lower, it absorbs reactive power (inductive mode). The current capability of a STATCOM is nearly independent of system voltage, making it highly effective during voltage sags or faults. The device exhibits superior dynamic performance, lower harmonic distortion, and smaller physical size compared to an SVC. Although its capital cost is higher, STATCOMs have become indispensable in renewable-energy integration, wind-farm voltage stabilization, and high-speed railway traction systems where rapid voltage control is essential.

In addition to shunt compensation, series compensation is another important technique used to improve power transfer capability and system stability. By inserting a capacitive element in series with the transmission line, the effective line reactance is reduced, thereby increasing the power transfer according to the power-angle relationship.

$$P = \frac{V_s V_r}{X} \sin \delta.$$

However, fixed series capacitors have limited flexibility and may cause subsynchronous resonance (SSR) problems with turbine-generator shafts. The introduction of the Thyristor-Controlled Series Capacitor (TCSC) addressed these limitations by enabling dynamic and continuous control of series compensation. A TCSC comprises a series capacitor

shunted by a Thyristor-Controlled Reactor (TCR). By adjusting the firing angle of the thyristors, the effective reactance of the TCR is varied, which in turn modifies the net impedance of the combined branch. The TCSC can operate in capacitive boost mode, where it increases power transfer; in inductive mode, where it limits current during faults; or in bypass mode, where it protects itself from overvoltages. In practice, TCSCs not only enhance steady-state power transfer but also provide transient stability improvement and oscillation damping. They are frequently employed in long EHV transmission corridors connecting large generation centers to load centers. More recently, with the advent of voltage-source converter technology, the Static Synchronous Series Compensator (SSSC) emerged as a more sophisticated alternative. The SSSC injects a controllable AC voltage in series with the transmission line through a coupling transformer. By varying the amplitude and phase angle of the injected voltage relative to the line current, it can emulate capacitive or inductive behavior, effectively controlling the real and reactive power flow. Because the converter voltage is generated electronically, the SSSC can maintain its reactive output even when system voltage drops significantly, something conventional series capacitors cannot achieve. Moreover, if equipped with an energy-storage device or DC link, the SSSC can exchange real power with the AC system, further enhancing its versatility. Its response is extremely fast, its operation smooth and continuous, and it produces minimal harmonic distortion. However, due to its higher cost and complexity, the SSSC is generally used in strategic transmission corridors or inter-regional tie lines where superior performance justifies the investment.

The limitations of individual shunt or series controllers motivated the development of combined or hybrid FACTS controllers, which integrate both functionalities through coordinated operation. The most versatile of these is the Unified Power Flow Controller (UPFC), which combines the characteristics of a STATCOM and an SSSC through a common DC link. The UPFC can independently or simultaneously control voltage magnitude, phase angle, and line impedance, providing full power-flow control in the transmission line. Its two voltage-source converters—one connected in shunt and the other in series—exchange power through the shared DC capacitor. The shunt converter primarily regulates bus voltage and DC-link voltage by injecting or absorbing reactive current, while the series converter controls power flow by injecting a voltage of controllable magnitude and phase in series with the line. This coordination enables the UPFC to perform both reactive- and active-power compensation dynamically, making it the most powerful and flexible member of the FACTS family. Other combined devices include the Interline Power Flow Controller (IPFC), which coordinates multiple SSSC units in different transmission lines, and the Generalized Unified Power Flow Controller (GUPFC), which extends the concept to multiple buses. These advanced devices facilitate congestion management, voltage stabilization, and optimal utilization of existing transmission infrastructure.

From a system-operation perspective, reactive power compensation using FACTS devices offers numerous

benefits. It improves voltage stability by maintaining bus voltages within prescribed limits during load variations and contingencies. It enhances transient stability by providing rapid voltage support during faults and by controlling power oscillations. It also increases steady-state power-transfer capacity by dynamically controlling line reactance and phase angles. Moreover, by compensating reactive power locally, FACTS devices reduce transmission losses and improve voltage regulation at distant load centers. In interconnected networks, they enable flexible control of loop flows and reduce the risk of cascading outages. Economically, they defer the need for new transmission lines by optimizing the utilization of existing ones. In renewable-rich grids, FACTS devices play a crucial role in mitigating voltage fluctuations caused by intermittent solar and wind generation. Their fast-acting control algorithms, often integrated with phasor-measurement-unit (PMU) data and digital control systems, enable real-time system optimization and adaptive voltage-reactive (Volt-VAR) management.

Technologically, the continuous improvement in semiconductor devices and converter topologies has significantly enhanced the performance of reactive-power compensation systems. Early thyristor-based FACTS controllers provided only reactive-power control, whereas modern voltage-source-converter-based systems can handle both real and reactive power interchange. The introduction of Modular Multilevel Converters (MMCs) has further improved converter efficiency, scalability, and harmonic performance, enabling FACTS devices to operate at higher voltages with reduced filter requirements. The integration of energy storage systems (such as supercapacitors or batteries) with STATCOMs and SSSCs has expanded their capabilities to provide fast frequency response and transient energy support. Moreover, the combination of FACTS technology with wide-area measurement systems (WAMS) and smart-grid control platforms allows coordinated operation across multiple devices, thereby maximizing system-level benefits rather than local optimization alone.

The theoretical foundation of reactive-power compensation through FACTS devices can also be explained using power-flow equations and phasor relationships. The real and reactive power transferred over a transmission line are given by.

$$P = \frac{V_s V_r}{X} \sin \delta, Q = \frac{V_s (V_s - V_r \cos \delta)}{X},$$

Where

V_s and V_r are the sending and receiving end voltages, X is the line reactance, and δ is the power angle. It is evident that the transmitted power depends inversely on X and directly on $\sin \delta$. Therefore, by controlling the effective line reactance (through TCSC or SSSC), the phase angle (through UPFC or Phase Shifting Transformer), or the voltage magnitude (through SVC or STATCOM), one can dynamically regulate both real and reactive power flow. This capability forms the essence of FACTS technology — flexible, continuous, and electronically controlled power transmission without the need

for mechanical switching or additional conductors. In practice, control algorithms based on proportional-integral (PI), model-predictive, or adaptive neural control are employed to maintain the desired operating point under varying load and fault conditions.

Despite their numerous advantages, the deployment of FACTS controllers for reactive-power compensation is not without challenges. High capital cost, complex control coordination, and the requirement of high-speed protection and communication systems can limit their widespread application in developing regions. However, with the continuing decline in semiconductor prices and advancements in digital control platforms, the cost-benefit ratio is steadily improving. Furthermore, hybrid configurations that combine fixed capacitors with smaller-rated dynamic devices (such as SVC plus STATCOM) provide a cost-effective compromise between performance and economics. In future smart-grid architectures, reactive-power compensation will evolve beyond centralized installations to distributed VAR control, where smaller FACTS devices are embedded throughout the network, including at renewable-generation terminals, microgrids, and even distribution feeders. This distributed approach will enable fine-grained voltage regulation and enhance overall grid resilience.

Reactive-power compensation through FACTS devices constitutes a cornerstone of modern power-system operation and control. By enabling rapid, smooth, and flexible control of voltage and reactive power, FACTS technology ensures stable and efficient operation of high-voltage AC networks under both steady-state and dynamic conditions. Shunt devices such as SVC and STATCOM provide voltage regulation and reactive-power support at substations and generation buses; series devices like TCSC and SSSC enhance power-transfer capability and stability margins; and combined devices like UPFC offer the most comprehensive solution for full power-flow control. The continuous evolution of power electronics, converter design, and control intelligence continues to expand the capabilities of these systems. As electric grids transition toward higher renewable-energy penetration, decentralized generation, and smart-grid interconnectivity, the role of FACTS in reactive-power compensation will become even more critical. Ultimately, FACTS controllers not only improve technical performance but also enable economic and environmental sustainability by maximizing existing infrastructure, reducing transmission bottlenecks, and enhancing power quality in the rapidly evolving landscape of electrical power engineering.

➤ Voltage Stability and Control Enhancement

In modern large interconnected power systems, voltage stability has become one of the most critical issues affecting system reliability, security, and economic operation. Voltage instability refers to the inability of a power system to maintain acceptable voltages at all buses under normal conditions and after disturbances, and in extreme cases leads to voltage collapse — a progressive drop in voltage that cannot be arrested, ultimately causing large-scale blackouts. The root cause of such instability is often an imbalance between

reactive-power supply and demand, insufficient dynamic voltage control, weak or heavily loaded transmission corridors, and the increasing penetration of non-synchronous, variable renewable generation that alter reactive power flows and system inertia. Traditional methods for maintaining voltage stability—such as switched capacitors or reactors, mechanical tap-changers, synchronous condensers—while still useful, are increasingly inadequate for the fast dynamic environment of today's grids. In this context, the advent of FACTS devices has offered a transformative means of enhancing voltage stability and control by providing rapid, flexible, and electronically controlled modulation of network parameters—voltage magnitude, impedance, phase angle—and thereby improving the system's ability to ride through disturbances, maintain loadability margins, and operate closer to thermal or stability limits without compromising security.

The fundamental mechanism by which voltage instability arises can be explained as follows: under increasing load or a disturbance, the consumption of reactive power increases (especially by inductive loads and the reactive demands of connected synchronous machines). If the system cannot supply sufficient reactive support locally or if the network is too weak (high impedance paths, long lines, limited shunt resources), the bus voltages begin to drop. As voltage drops, certain loads (especially motor loads) draw more current to maintain power, this drives further voltage drop due to line & transformer impedance, causing a vicious cycle of decreasing voltage and increasing reactive demand. If unchecked, the system reaches a point of no return where even small additional load or further loss of reactive support triggers collapse. The voltage-stability margin is defined by the maximum loading (or reactive demand) the system can sustain before entering this region of instability. Enhancing this margin is the principal goal of voltage-stability control. This enhancement entails keeping voltages within acceptable bounds, providing fast and adequate reactive power, controlling power flows so that weak corridors aren't overloaded, and dynamically adapting to contingencies and changing generation/ load patterns.

FACTS devices play a central role in this enhancement by virtue of their ability to rapidly modulate key parameters in the network. These parameters include the bus voltage magnitude (via shunt compensation), the effective line impedance (via series compensation), and the phase-angle between sending and receiving ends (via phase-shifting or series devices). In essence, the real and reactive power flows in a line can be expressed in approximate form by the equations.

$$P \approx \frac{V_s V_r}{X} \sin \delta, Q \approx \frac{V_r}{X} (V_s \cos \delta - V_r)$$

Where V_s and V_r are the magnitudes of the sending-end and receiving-end voltages, X is the line reactance, and δ is the phase-angle difference. From these expressions, it is clear that by controlling V_s , V_r , X , or δ , one can influence both

active and reactive power flow and indirectly voltage profiles throughout the network. FACTS devices make these controls continuous, fast, and electronically tunable, in contrast with older, discrete, slower mechanical methods. The ability to tune these variables during steady-state, during contingencies, and during transients gives the system operator a powerful "knob" to keep the system stable.

Consider the role of shunt-connected FACTS converters such as the Static VAR Compensator (SVC) or the Static Synchronous Compensator (STATCOM). These devices sit at bus locations, and inject or absorb reactive power almost instantaneously as needed. When a bus voltage begins to drop due to increased loading or reactive demand, the shunt device can supply reactive power (capacitive mode) to lift the voltage, thus arresting the decline and restoring acceptable voltage. Conversely, if the voltage is excessive, the device can absorb reactive power (inductive mode) to stabilise the voltage. By providing such local and fast reactive support the devices increase the local voltage stability margin, support weak buses, and mitigate cascading voltage collapse phenomena. Because of their dynamic nature, these FACTS devices help the system to remain in the stable region for larger load increments or harsher contingencies than would be possible without them. Many studies show that the presence of such devices increases the loading margin before instability and reduces the likelihood of collapse under system stress. Indeed, the literature indicates that FACTS devices "enable tighter continuous control of power flows maintaining a voltage that is within acceptable ranges at load buses mimproving safety measures, and operating electrical systems close to their capacity limits".

Series-connected FACTS devices such as the Thyristor-Controlled Series Capacitor (TCSC) or the Static Synchronous Series Compensator (SSSC) affect voltage stability in a complementary way. By dynamically adjusting the effective line reactance or injecting a controllable series voltage, these devices control the power-flow distribution across the network, relieve heavily burdened lines, and reduce the stress on weak corridors that are prone to voltage collapse. For example, when a line's impedance is reduced via series compensation, the transfer capability increases, sending higher real power to loads without causing excessive voltage drop. This reduces the loading on alternative lines (which might otherwise be used during contingencies) and thus mitigates the risk of voltage instability triggered by overload or line loss. A TCSC, by adjusting the series compensation level, prevents abrupt jumps in load flows, improves damping of oscillations, and thus enhances dynamic and transient stability a key component of maintaining voltage stability under disturbances. Similarly, an SSSC can inject a series voltage in quadrature with line current to control reactive or real power flow, thereby giving the operator direct control over line stress, voltage profiles along the line, and phase angle differences which influence stability margins.

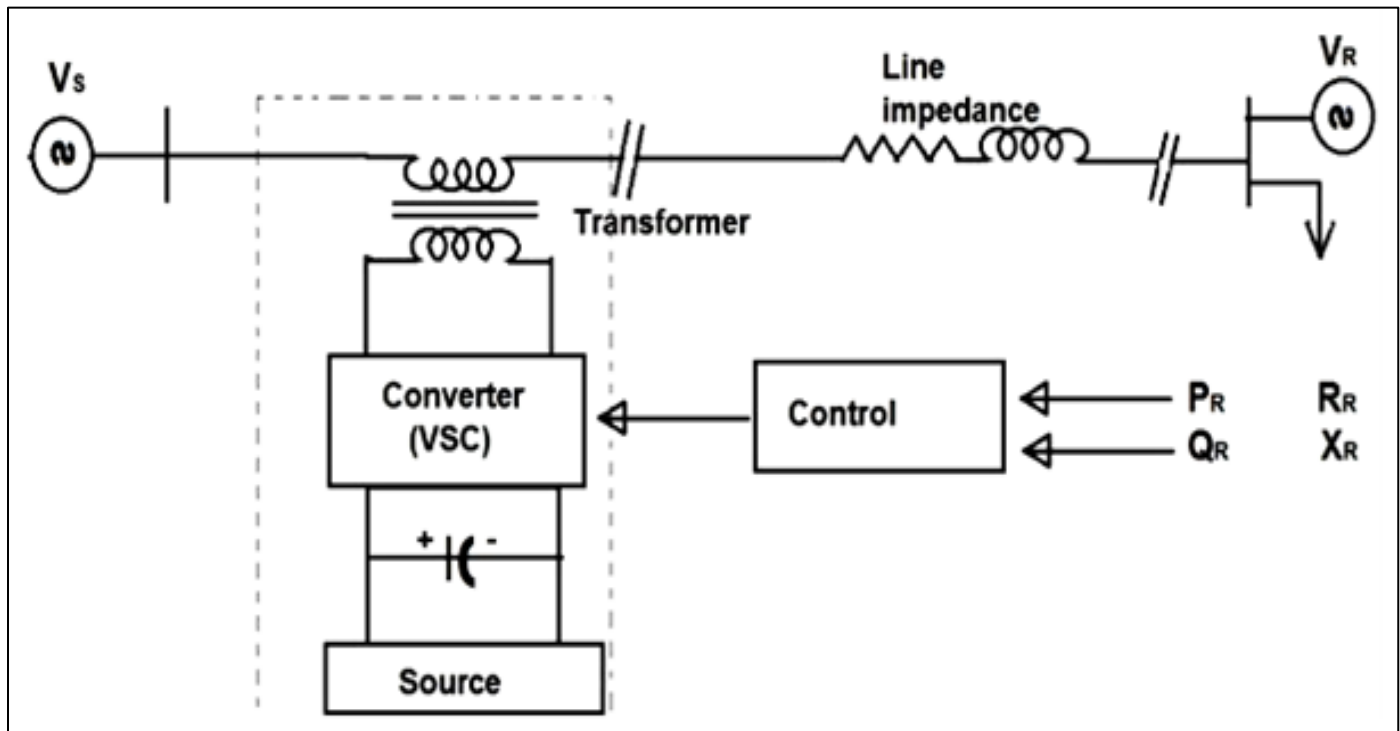


Fig 2 SSSC

Beyond shunt and series devices alone, combined or hybrid FACTS controllers – such as the Unified Power Flow Controller (UPFC) – provide the most comprehensive toolset for voltage stability enhancement. A UPFC integrates both shunt- and series-converter capabilities, sharing a common DC link, enabling simultaneous control of bus voltage, line impedance, and phase angle. In a voltage-stability context this means that the UPFC can provide reactive support to a weak bus, adjust the phase angle to relieve overloaded lines, and modulate line impedance to achieve optimal power-flow patterns, all in real time. This multiplicity of controls greatly enhances the system’s ability to respond to contingencies, shift flows away from vulnerable corridors, maintain voltages within safe bounds, and increase the loadability margin significantly compared to systems without such devices. The technical literature asserts that FACTS controllers “boost voltage stability capabilities to control the linked parameters properly improve the dynamic and transient behavior of the system and transmit the most significant amount of power in emergencies such as line outages.”

Implementation of FACTS devices for voltage-stability control involves both steady-state and dynamic considerations. In the steady-state domain, placement and sizing of FACTS devices must be optimized to enhance the static voltage-stability margin—the maximum load or reactive power the system can handle without voltage collapse. In that sphere, voltage-stability indices (e.g., loadability margin indices, continuation power-flow results) and weak-bus detection methods are used to determine where to locate shunt or series compensators. For example, one study used the voltage collapse proximity index (VCPI) to identify weak buses and then placed STATCOM and TCSC devices to maintain voltage profiles during increased load. By locating the FACTS devices at critical points (weak buses,

stressed corridors, near large reactive-power-demanding loads or remote load centres) one ensures that reactive support is available exactly where needed to arrest voltage decline or collapse. The steady-state benefit is an increase in the margin before instability, allowing higher loading, greater transfer capability, and improved bus-voltage profiles under normal and contingency conditions.

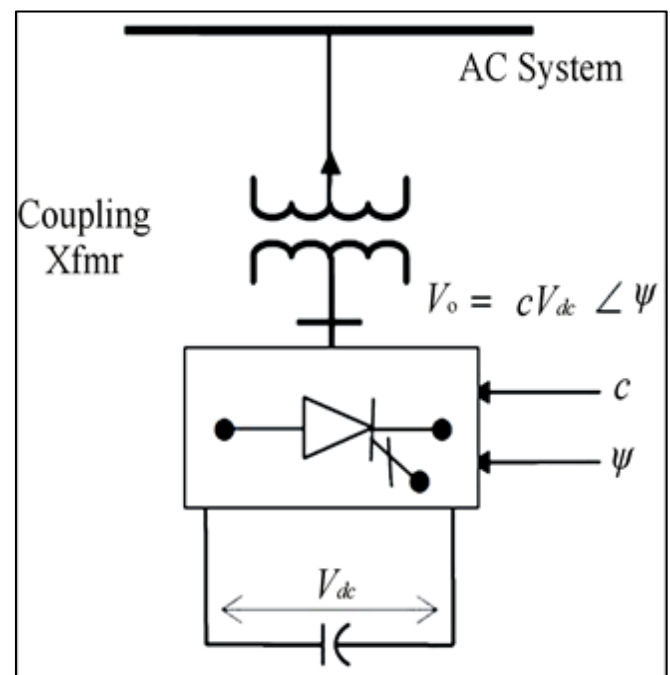


Fig 3 STATCOM

In the dynamic domain, voltage stability encompasses not only static margins but also the system’s ability to respond to disturbances (faults, line outages, large load

changes, generator tripping). Here, FACTS devices offer real advantage because of their fast-acting nature. For example, when a fault causes a sudden voltage dip, a STATCOM can inject reactive current within a few milliseconds, helping to support the voltage, reduce the depth of the sag, and avoid the system going into the unstable region. Similarly, series devices can modulate line impedance or voltage within a cycle to reduce oscillations, damp angular swings, and control power flows away from the stressed system portions. The combined action of such devices helps the system ride through disturbances without entering the unstable zone, thereby improving transient voltage stability and avoiding voltage collapse triggered by cascading events. The literature supports this view: e.g., “FACTS devices are helpful for maintaining voltage stability during load variation, for increasing loadability of power system as a whole and to maintain stability of power system.

From a control-system viewpoint, the integration of FACTS devices into voltage stability enhancement involves coordinated control algorithms, real-time monitoring (often via phasor-measurement units, PMUs), and system-wide optimization. Modern schemes incorporate wide-area measurement systems that feed into adaptive FACTS control setpoints, enabling devices to respond to system-wide voltage events rather than just local voltage drops. For example, model-free wide-area voltage control methods using PMU data have been proposed where FACTS devices' reference points are adjusted online based on sensitivity matrices estimated from measurements. This real-time coordination is essential because voltage instability is fundamentally system-wide phenomenon—local control alone may not suffice if the disturbance propagates or if the system is heavily interconnected and rerouting of flows occurs.

Despite their many advantages, the use of FACTS devices for voltage stability enhancement is not without challenges. First, the high capital cost of advanced FACTS (especially voltage-source converter types like STATCOMs, SSSCs, UPFCs) remains a major barrier in some regions. Second, the control coordination among multiple devices in large systems can be complex: decisions about setpoints, modes of operation, interactions between devices, and overarching stability control must be carefully engineered. Third, the correct placement and sizing require detailed steady-state and dynamic studies (load-flow, continuation power-flow, time-domain simulation), which introduce planning complexity. Fourth, there is often the need for high-speed communication and measurement infrastructure (PMUs, SCADA, wide-area monitoring) to enable real-time control; this increases system complexity and cybersecurity/communication reliability concerns. Fifth, while FACTS devices improve stability, they do not eliminate the root causes of weak grids—such as inadequate generation reactive support, long radial lines, poor network topology or excessive load growth beyond planning. Thus they must be complemented by sound system planning, reactive-power

reserve criteria, contingency preparation, and network reinforcement.

➤ *Power System Performance Improvement*

The modern electrical power system is a vast, complex, and highly interconnected network consisting of generation plants, transmission lines, substations, and distribution networks designed to supply electric power reliably and efficiently to millions of consumers. However, the increasing demand for electricity, the geographical separation between generation and load centers, and the integration of renewable energy sources have imposed severe stress on existing transmission infrastructures. This has resulted in challenges such as voltage instability, power-flow congestion, poor dynamic performance, and reduced reliability margins. Traditionally, the performance of a power system was improved by building new transmission lines or upgrading existing ones. Yet, such solutions are often constrained by environmental, economic, and right-of-way limitations. The development of Flexible AC Transmission System (FACTS) technology, based on high-power electronics, has emerged as a revolutionary approach to enhance system performance without expanding physical infrastructure. FACTS devices enable real-time control of key electrical parameters voltage magnitude, phase angle, and line impedance—thus providing unprecedented flexibility, stability, and efficiency in power-system operation.

One of the most significant aspects of power-system performance improvement through FACTS lies in enhancing voltage stability and reactive-power management. In a conventional system, reactive power is mainly supplied by fixed capacitors or synchronous condensers, which cannot respond rapidly to sudden voltage dips or load changes. FACTS devices such as the Static VAR Compensator (SVC) and the Static Synchronous Compensator (STATCOM) offer fast, continuous control of reactive power and voltage at critical buses. The SVC uses a combination of Thyristor-Controlled Reactors (TCRs) and Thyristor-Switched Capacitors (TSCs) to inject or absorb reactive power depending on system voltage. When voltage drops, the SVC operates in capacitive mode to provide reactive support; when voltage rises, it operates in inductive mode to absorb excess vars. Similarly, the STATCOM, based on Voltage-Source Converter (VSC) technology, synthesizes a controllable AC voltage that can independently supply or absorb reactive current regardless of the system voltage level. Because of its converter-based design, the STATCOM provides faster response, better performance under low-voltage conditions, and reduced harmonic distortion compared to SVCs. The result is improved voltage stability, enhanced loadability, and better dynamic response during disturbances such as faults or load variations. The presence of shunt FACTS devices increases the local voltage-stability margin and allows utilities to operate transmission lines closer to their design capacity while maintaining acceptable voltage levels.

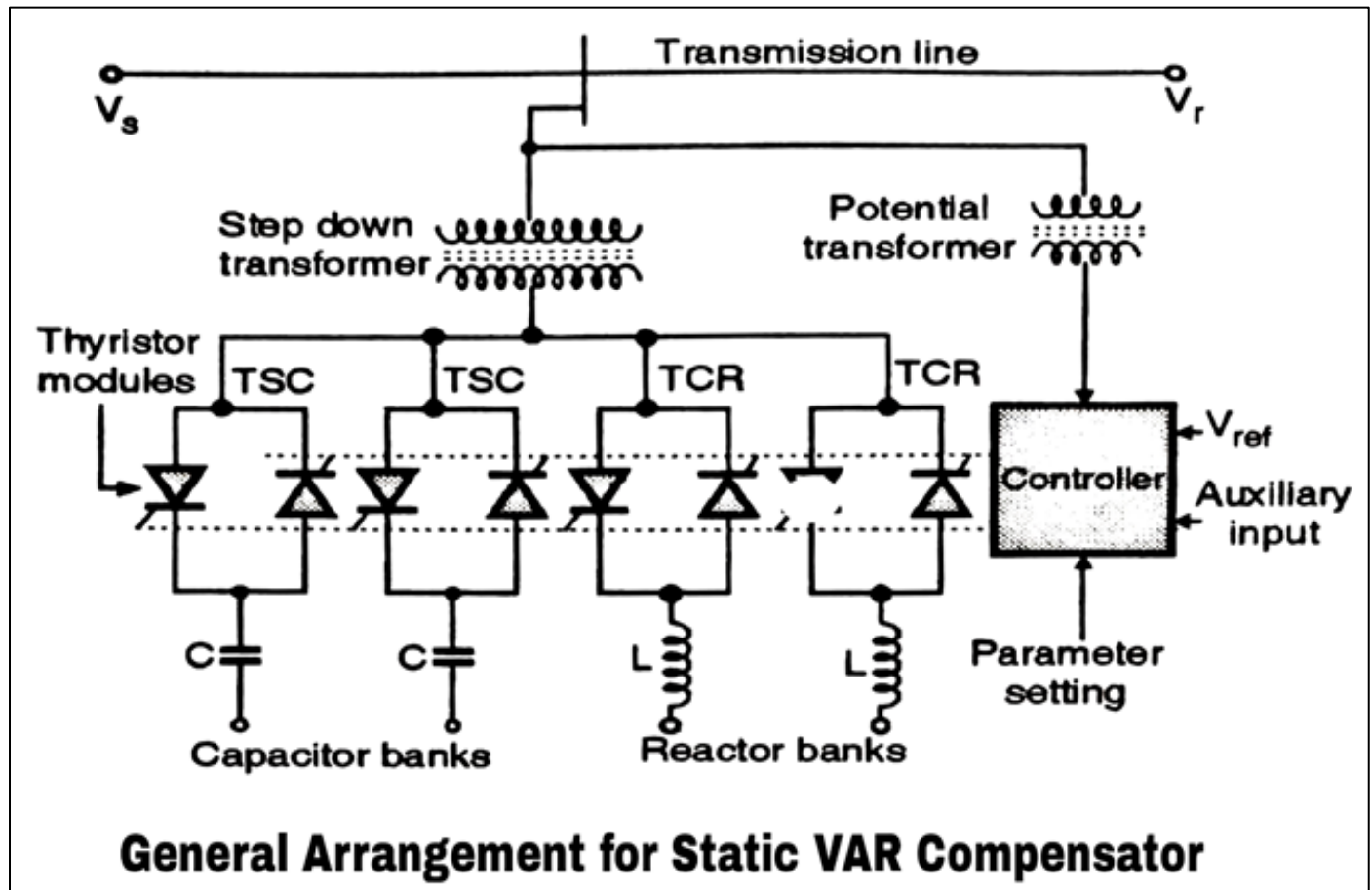


Fig 4 SVC

Another major contribution of FACTS controllers is improvement in power-flow control and congestion management. In a large interconnected grid, it is common for certain transmission lines to become overloaded while parallel paths remain underutilized due to the physical laws governing power flow. FACTS devices provide a means to redistribute power flows dynamically, thereby balancing loading among parallel corridors and avoiding thermal overloads. Series-connected devices such as the Thyristor-Controlled Series Capacitor (TCSC) and the Static Synchronous Series Compensator (SSSC) play a key role here. The TCSC controls the effective line reactance by varying the firing angle of thyristor valves connected across a series capacitor, allowing smooth adjustment of line impedance. Reducing the reactance increases the power-transfer capability of the line and helps control the direction and magnitude of power flow between interconnected areas. The SSSC, on the other hand, injects a controllable AC voltage in series with the line, independent of line current, thus providing direct control of real and reactive power. Through these mechanisms, series FACTS controllers relieve transmission congestion, minimize transmission losses, and enhance the system's steady-state stability limit. They also improve damping of inter-area power oscillations by modulating the power flow in synchronism with the oscillation frequency.

Transient and dynamic stability enhancement represents another critical performance improvement achieved through

FACTS technology. During a disturbance such as a short circuit or generator tripping, system variables (rotor angle, voltage, and current) undergo rapid changes. The ability of the system to return to a stable operating condition after the disturbance defines its transient stability. FACTS devices contribute to transient stability by providing rapid control actions that counteract the effects of disturbances. For example, a TCSC can modulate line impedance to control power flow and maintain synchronism between generators, while a STATCOM can inject reactive current to support voltage during and immediately after the fault. A Unified Power Flow Controller (UPFC), combining both series and shunt compensation within a single coordinated structure, offers the most versatile dynamic control. It can simultaneously control bus voltage, phase angle, and line impedance, providing comprehensive damping and power-flow regulation. By mitigating transient swings and improving voltage recovery, FACTS controllers increase the critical clearing time of faults and enable the system to withstand larger disturbances without losing synchronism.

FACTS controllers also significantly contribute to system reliability and security. In a highly stressed power system, contingencies such as line outages or sudden load increases can easily cause voltage instability or cascading failures. FACTS devices help maintain reliability by dynamically redistributing power, providing fast voltage support, and controlling reactive power exchange between regions. They offer additional operational flexibility to grid

operators, allowing them to maintain N-1 contingency security without excessive reserves. Furthermore, by stabilizing power oscillations and improving damping, FACTS controllers reduce the likelihood of widespread blackouts. For instance, coordinated operation of multiple FACTS devices across different network locations can prevent power swings from propagating and isolate disturbances before they escalate. In this way, FACTS technology strengthens both the preventive and corrective control mechanisms of power-system operation.

➤ *Advantages*

FACTS systems exhibit several advantages including improved transmission efficiency, flexible power flow control, enhanced grid stability, and reduced environmental impact. They enable large-scale renewable integration, support voltage stability across networks, and enhance system reliability without requiring new transmission infrastructure. Additionally, FACTS reduces dependency on long AC transmission corridors and mitigates technical limitations such as reactive losses and voltage collapse concerns.

➤ *Applications*

FACTS systems are widely applied in:

- Urban load centers requiring enhanced voltage support
- Industrial areas with inductive loads (arc furnaces, motors)
- Renewable energy integration (wind, solar)
- Congested transmission corridors
- Weak grid areas requiring stability enhancement
- Power quality improvement in sensitive facilities

III. CONCLUSION

The control of reactive power through Flexible AC Transmission System (FACTS) controllers has revolutionized the way modern power systems maintain voltage stability, improve efficiency, and enhance overall performance. Reactive power, though non-working in nature, plays a vital role in sustaining the electromagnetic fields essential for energy conversion and transmission. The inability to balance reactive power demand and supply often leads to voltage instability, system losses, and reduced reliability. FACTS controllers such as the Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), and Unified Power Flow Controller (UPFC) offer dynamic, continuous, and rapid control of reactive power, enabling real-time voltage regulation and optimized power flow. By injecting or absorbing reactive current as required, shunt devices like SVC and STATCOM stabilize bus voltages and improve power factors, while series devices such as TCSC and SSSC modulate line reactance to control power transfer and enhance loadability. Combined controllers like UPFC integrate both functions to achieve comprehensive voltage and power-flow control, making them the most versatile among FACTS families. The integration of these controllers reduces transmission losses, mitigates voltage

collapse risks, and enhances transient as well as dynamic stability, particularly under faulted or heavily loaded conditions. Moreover, FACTS devices support renewable-energy integration by compensating for variable reactive power output, ensuring grid reliability under fluctuating conditions. With advancements in converter technology and intelligent control algorithms, FACTS-based reactive power control is evolving toward smarter, faster, and more efficient solutions. Ultimately, the strategic application of FACTS controllers ensures that modern power systems operate with optimal voltage profiles, higher power transfer capability, and enhanced security meeting the growing energy demands of a sustainable, stable, and flexible electricity network.

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AUTHOR'S PROFILE

B Kishore is completed SSC at New Millennium High School, Suryapet and studied Diploma at JNGP, Ramanthpur. He is pursuing BE Electrical and Electronics Engineering at Methodist College of Engineering, Hyderabad



S VishwaTeja is completed SSC at Telangana state Model school, Kathalapur, and studied diploma at Govt. Polytechnic College Nizamabad. He is pursuing BE Electrical and Electronics Engineering at Methodist College of Engineering, Hyderabad



N Ramakrishna is completed SSC at Regina carmeli convent school, Palwancha and studied diploma at KLR College of Engineering and Technology, Palwancha. He is pursuing BE Electrical and Electronics Engineering at Methodist College of Engineering, Hyderabad.



S Umesh is completed SSC at cramel convent High School, Mancherial and studied diploma at VMR Polytechnic, Warangal. He is pursuing BE Electrical and Electronics Engineering at Methodist College of Engineering, Hyderabad



B Sharath is completed SSC at St.Johns High School, Ramanthapur and studied diploma at Mahaveer Institute of science and Technology, Bandlaguda. He is pursuing BE Electrical and Electronics Engineering at Methodist College of Engineering, Hyderabad.



B Varshith is completed school at Ravindra High School and studied diploma at SVS Group of Institutions, Hanmakonda. He is pursuing BE Electrical and Electronics Engineering at Methodist College of Engineering, Hyderabad.